

# Variation of the baryon-to-photon ratio due to decay of dark matter particles

E. O. Zavarygin<sup>1,2\*</sup> and A. V. Ivanchik<sup>1,2\*\*</sup>

<sup>1</sup>*Ioffe Institute, ul. Politekhnikeskaya 26, St. Petersburg, 194021 Russia*

<sup>2</sup>*Peter the Great St.Petersburg Polytechnic University, ul. Politekhnikeskaya 29, St. Petersburg, Russia*

Received 05 December, 2014

## Abstract

The influence of dark matter particle decay on the baryon-to-photon ratio has been studied for different cosmological epochs. We consider different parameter values of dark matter particles such as mass, lifetime, the relative fraction of dark matter particles. It is shown that the modern value of the dark matter density  $\Omega_{\text{CDM}} = 0.26$  is enough to lead to variation of the baryon-to-photon ratio up to  $\Delta\eta/\eta \sim 0.01 \div 1$  for decays of the particles with masses  $10 \text{ GeV} \div 1 \text{ TeV}$ . However, such processes can also be accompanied by emergence of an excessive gamma ray flux. The observational data on the diffuse gamma ray background are used to making constraints on the dark matter decay models and on the maximum possible variation of the baryon-to-photon ratio  $\Delta\eta/\eta \lesssim 10^{-5}$ . Detection of such variation of the baryon density in future cosmological experiments can serve as a powerful means of studying properties of dark matter particles.

**Key words.** cosmology, dark matter, baryonic matter

## 1. INTRODUCTION

In the last decade, cosmology has passed into the category of precision sciences. Many cosmological parameters are currently determined with a high precision that occasionally reaches fractions of a percent (Ade et al. 2014). One of such parameters is the baryon-to-photon ratio  $\eta \equiv n_b/n_\gamma$ , where  $n_b$  and  $n_\gamma$  are the baryon and photon number densities in the Universe, respectively. In the standard cosmological model, the present value of  $\eta$  is assumed to have been formed upon completion of electron-positron annihilation several seconds after the Big Bang and has not changed up to now.

The value of  $n_\gamma$  associated with the cosmic microwave background (CMB) photons is defined by the well-known relation

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} \left( \frac{kT}{\hbar c} \right)^3 = 410.73 \left( \frac{T}{2.7255 \text{ K}} \right)^3 \text{ cm}^{-3},$$

where  $\zeta(x)$  is the Riemann zeta function,  $k$  is the Boltzmann constant,  $\hbar$  is the Planck constant,  $c$  is the speed of light, and  $T$  is the CMB temperature at the corresponding epoch. The CMB temperature is currently determined with a high accuracy and is  $T_0 = 2.7255(6) \text{ K}$  at the present epoch (Fixsen 2009); for other epochs, it is expressed by the relation  $T = T_0(1+z)$ , where  $z$  is the cosmological redshift at the corresponding epoch. Thus, given  $n_\gamma$ , a relation between the parameter  $\eta$  and  $\Omega_b$ , the relative baryon density in the Universe, can be obtained (Steigman 2006):

$$\eta = 273.9 \times 10^{-10} \Omega_b h^2,$$

where  $h = 0.673(12)$  is the dimensionless Hubble parameter at the present epoch (Ade et al. 2014). According to present views, the baryon density, which is the density of ordinary matter (atoms, molecules, planets and stars, interstellar and intergalactic gases), does not exceed 5% of the entire matter filling the Universe, while 95% of the density in the Universe is composed of unknown forms of matter/energy that manifest themselves (for the time being) gravitationally (see, e.g., Gorbunov and Rubakov 2008).

At present, observations allow  $\Omega_b$  to be independently estimated for four cosmological epochs:

- (i) the epoch of Big Bang nucleosynthesis ( $z_{\text{BBN}} \sim 10^9$ ; see, e.g., Steigman et al. 2007);
- (ii) the epoch of primordial recombination ( $z_{\text{PR}} \simeq 1100$ ; see, e.g., Ade et al. 2014);
- (iii) the epoch associated with the Ly $\alpha$  forest ( $z \sim 2 \div 3$ ; i.e.,  $\sim 10$  Gyr ago; see, e.g., Rauch 1998; Hui et al. 2002);
- (iv) the present epoch ( $z = 0$ ; see, e.g., Fukugita and Peebles 2004).

For the processes at the epochs of Big Bang nucleosynthesis and primordial recombination,  $\eta$  is one of the key parameters determining their physics. For these epochs, the methods of estimating  $\eta$ , (i) comparing the observational data on the relative abundances of the primordial light elements (D,  $^4\text{He}$ ,  $^7\text{Li}$ ) with the predictions of the Big Bang nucleosynthesis theory and (ii) analyzing the CMB anisotropy, give the most accurate estimates of  $\eta$  to date that coincide, within the observational error limits:  $\eta_{\text{BBN}} = (6.0 \pm 0.4) \times 10^{-10}$  (Steigman 2007) and  $\eta_{\text{CMB}} = (6.05 \pm 0.07) \times 10^{-10}$  (Ade et al. 2014). This argues for the correctness of the adopted model of the Universe and for the validity of the standard physics used in theoretical calculations. However, it should be noted that at present, as the accuracy of observations

\* E-mail: e.zavarygin@gmail.com

\*\* E-mail: iav@astro.ioffe.ru

increases, some discrepancy between the results of observations and the abundances of the primordial elements predicted in the Big Bang nucleosynthesis theory has become evident. The “lithium problem” is well known (see, e.g., Cyburt et al. 2008); not all is ideal with helium and deuterium (for a detailed discussion of these problems, see Ivanchik et al. 2015). These inconsistencies can be related both to the systematic and statistical errors of experiments and to the manifestations of new physics (physics beyond the standard model).

The determination of  $\Omega_b$  and the corresponding  $\eta$  at epochs (iii) and (iv) has a considerably lower accuracy. The value of  $\eta$  measured for the epoch associated with the Ly $\alpha$  forest coincides, by an order of magnitude, with  $\eta_{\text{BBN}}$  and  $\eta_{\text{CMB}}$ , but, at the same time, is also strongly model-dependent (e.g., Hui et al. 2002). The measured  $\Omega_b$  and  $\eta$  at the present epoch are at best half those predicted by Big Bang nucleosynthesis calculations and CMB anisotropy analysis. The so-called problem of missing baryons (see, e.g., Nicastro et al. 2008) is associated with this.

It is hoped that further observations and new experiments will allow  $\Omega_b$  for different cosmological epochs and the corresponding  $\eta$  to be determined with a higher accuracy. In turn, this can become a powerful tool for investigating the physics beyond the standard model, where the values of  $\eta$  for different cosmological epochs can be different. Constraints on the deviation of  $\eta$  allow various theoretical models admitting such a change to be selected.

In this paper, we discuss the possibility of a change in  $\eta$  on cosmological time scales attributable to the decays of dark matter particles. For example, supersymmetric particles (see, e.g., Jungman et al. 1996; Bertone et al. 2004; and references therein) can act as such particles; some of them can decay into the lightest stable supersymmetric particles and standard model particles (baryons, leptons, photons, etc.; see, e.g., Cirelli et al. 2011):

$$X \rightarrow \chi + \dots \begin{cases} \gamma + \gamma + \dots \\ p + \bar{p} + \dots, \end{cases} \quad (1)$$

where  $X$  and  $\chi$  are unstable and stable dark matter particles, respectively. This can lead to a change in  $\eta$ .

The currently available observational data suggest that the dark matter density in the Universe is approximately a factor of 5 larger than the baryon density:  $\Omega_{\text{CDM}} \simeq 5\Omega_b$ , i.e., the relation between the number density of dark matter particles and the number densities of baryons and photons in the Universe is  $n_{\text{CDM}} \simeq 5(m_b/m_{\text{CDM}})n_b = 5(m_b/m_{\text{CDM}})n_\gamma\eta$ . Assuming that the changes in the number densities of various types of particles in the decay reactions of dark matter particles are related as  $\Delta n_{\text{CDM}} \sim \Delta n_b$  and  $\Delta n_{\text{CDM}} \sim \Delta n_\gamma$ , it is easy to see that the parameter  $\eta$  is most sensitive precisely to the change in baryon number density. In the decays of dark matter particles with masses  $m_{\text{CDM}} \sim 10 \text{ GeV} - 1 \text{ TeV}$ , the change in  $\eta$  as a result of the change in baryon number density could reach  $\Delta\eta/\eta \sim 0.01 - 1$ <sup>1</sup>. The change in photon number density

and the change in  $\eta$  attributable to it will be approximately billion times smaller. Therefore, in our paper we focused our attention on the possibility of a change in  $\eta$  due to the decays of dark matter particles with the formation of a baryon component.

Despite the negligible contribution to the change in  $\eta$  from the photon component, a comparison of the predicted gamma-ray background (dark matter particle decay products) with the observed isotropic gamma-ray background in the Universe can serve as an additional source of constraints on the decay models of dark matter particles. The photons produced by such processes are high-energy ones. The observational data on the isotropic gamma-ray background constrain their possible number in the Universe, which, in turn, narrows the range of admissible parameters of dark matter particles, determines the maximum possible number of baryons, the decay products of dark matter particles, and the corresponding change in the baryon-to-photon ratio in such decays. Thus, the observational data on the gamma-ray background, along with the cosmological experiments described above, serve as a source of constraints on the decay models of dark matter particles and on the possible change in  $\eta$ . Running ahead, we will say that at present the constraints from isotropic gamma-ray background observations are more severe than those following from cosmological experiments.

Depending on the lifetime of dark matter particles, a statistically significant change in  $\eta$  can occur at different cosmological epochs. We consider lifetimes  $\tau$  in the following range:  $t_{\text{BBN}} \ll \tau \lesssim t_0$ , where  $t_{\text{BBN}} \simeq 3 \text{ min}$  is the age of the Universe at the end of the epoch of Big Bang nucleosynthesis,  $t_0 \simeq 13.8 \text{ Gyr}$  is the present age of the Universe (Ade et al. 2014). The decays of dark matter particles with short lifetimes ( $\tau \lesssim t_{\text{BBN}}$ ) can change significantly the chemical composition of the Universe (see, e.g., Jedamzik 2004; Kawasaki et al. 2005). The available observational data on the abundances of the primordial light elements (D, <sup>4</sup>He, <sup>7</sup>Li) agree well with the predictions of Big Bang nucleosynthesis calculations, which, in turn, limits the possibility of such a change. For long lifetimes exceeding the present age of the Universe ( $\tau > t_0$ ), the change in  $\eta$  at the above four cosmological epochs will be so small that this will unlikely allow it to be detected without a significant improvement in observational capabilities.

## 2. THE BARYON-TO-PHOTON RATIO IN MODELS WITH PARTICLE DECAY

A large class of models with decaying dark matter particles suggests the existence of the lightest stable particle that we will designate as  $\chi$ . An unstable dark matter particle, which we will designate as  $X$ , will decay with time into a  $\chi$ -particle and standard model particles. There can be reactions of the type  $X \rightarrow \chi p \bar{p}$  among such reactions, whose influence on  $\eta$  is investigated in this paper<sup>2</sup>. A quantitative parameter characterizing the fraction of the decay channels of  $X$ -particles

example, D, He, etc.) are generated with a considerably lower probability.

<sup>2</sup> Since we consider cosmological time scales, all of the neutrons and antineutrons that are also produced in such decays transform into protons and antiprotons.

<sup>1</sup> Here and below, out of all baryons, we restrict ourselves to protons. This assumption is valid for obtaining estimates, because the bulk of the baryon density in the Universe is contained in the hydrogen nuclei, while heavier baryons (for

whose products are hadrons (in our case, these will be protons and antiprotons) in the total number of decay channels is the hadronic branching ratio  $B_h$ , which is  $B_h = 1$  in our case.

The currently available observational data argue for the absence (or a negligible amount) of relic antimatter (baryon-asymmetric Universe). For this reason, the parameter  $\eta$  in the standard cosmological model is defined as the ratio of the baryon number density to the photon number density. Since in our model the decays of X-particles will lead to the production of protons and antiprotons, we will define the parameter  $\eta$  as the ratio of the sum of the baryon and antibaryon number densities to the photon number density in the Universe:

$$\eta(z) = \frac{n_b(z) + n_{\bar{b}}(z)}{n_\gamma(z)} \quad (2)$$

$$= \frac{n_b^{\text{BBN}}(z) + \Delta n_p(z) + \Delta n_{\bar{p}}(z)}{n_\gamma^{\text{BBN}}(z)} = \eta_{\text{BBN}} + \Delta\eta(z),$$

where  $n_b^{\text{BBN}}$  and  $n_\gamma^{\text{BBN}}$  are the baryon and photon number densities corresponding to  $\eta_{\text{BBN}} = n_b^{\text{BBN}}/n_\gamma^{\text{BBN}}$ ;  $\Delta n_p(z)$  and  $\Delta n_{\bar{p}}(z)$  are the number densities of X-particle decay products: protons and antiprotons, respectively (in the model under consideration,  $\Delta n_p(z) = \Delta n_{\bar{p}}(z)$ , i.e., the generated baryonic charge is  $\Delta B = 0$ ). It is this value of (2) that would be measured when determining the speed of sound of the baryon-photon plasma at the epoch of CMB anisotropy formation in the case of proton and antiproton generation in accordance with the formula (see, e.g., Gorbunov and Rubakov 2010)

$$u_s^2 = \frac{\delta p}{\delta \rho} = \frac{c^2}{3(1 + 3\rho_{\text{BB}}/4\rho_\gamma)}, \quad (3)$$

where  $\rho_{\text{BB}} = \rho_B + \rho_{\bar{B}}$  is the sum of the baryon and antibaryon densities in the Universe. In the standard cosmological model, this quantity coincides with the baryon density of the Universe  $\rho_B$ . Thus, the baryon-to-photon ratio determined when analyzing the CMB anisotropy is also the ratio of the sum of the baryon and antibaryon number densities to the photon number density and has the following form in the presence of X-particle decay products:

$$\eta_{\text{CMB}} = \left. \frac{n_b(z) + n_{\bar{b}}(z)}{n_\gamma(z)} \right|_{z=z_{\text{PR}}} = \eta_{\text{BBN}} + \Delta\eta(z_{\text{PR}}), \quad (4)$$

Note that for very early decays the antiprotons being produced have time to annihilate with protons, and  $\eta$  again returns to its initial value  $\eta = \eta_{\text{BBN}}$ . The decays of X-particles with long lifetimes will occur in an already fairly expanded Universe; consequently, the antiprotons being produced may not have time to annihilate. Thus, the later  $\eta$  can differ from  $\eta_{\text{BBN}}$  and  $\eta_{\text{CMB}}$ . However, during the formation of a large-scale structure, when halos in which the density of matter exceeds considerably the average one is formed, an excess of antiprotons would lead to enhanced gamma-ray radiation from them.

### 3. INFLUENCE OF THE DECAY OF DARK MATTER PARTICLES ON THE CHANGE IN $\eta$

The evolution of the number densities of X-particles,  $\chi$ -particles, protons, and antiprotons in the Universe is described by the system of kinetic equations

$$\frac{dn_X}{dt} + 3Hn_X = -\Gamma n_X, \quad (5)$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \Gamma n_X, \quad (6)$$

$$\frac{dn_{p,\bar{p}}}{dt} + 3Hn_{p,\bar{p}} = -\langle\sigma v\rangle_{p\bar{p}}^{\text{ann}} n_p n_{\bar{p}} + B_h \Gamma n_X, \quad (7)$$

where Eq. (7) consists of two equations describing the evolution of the proton and antiproton number densities,  $n_p$  and  $n_{\bar{p}}$ , respectively;  $n_X$  and  $n_\chi$  are the number densities of X- and  $\chi$ -particles, respectively;  $H = \dot{a}/a$  is the Hubble parameter;  $a(t)$  is the scale factor;  $\Gamma = 1/\tau$  is the decay rate of X-particles;  $\langle\sigma v\rangle_{p\bar{p}}^{\text{ann}}$  is the product of the relative velocity  $v$  and proton-antiproton annihilation cross section  $\sigma_{\text{ann}}$  averaged over the momentum with a distribution function. In a wide energy range ( $10 \text{ MeV} \lesssim T_{\bar{p}} \lesssim 10 \text{ GeV}$ ), this quantity may be considered a constant,  $\langle\sigma v\rangle_{p\bar{p}}^{\text{ann}} = 10^{-15} \text{ cm}^3 \text{ s}^{-1}$  (see, e.g., Stecker 1967; Weniger et al. 2013). The parameters of the standard cosmological model presented in Table 1 are used to solve Eqs. (5)–(7).

**Table 1.** Cosmological parameters used in this paper

Parameter	Value	Reference <sup>1</sup>
$\Omega_R$	$5.46 \times 10^{-5}$	1
$\Omega_{\text{CDM}}$	0.265	2
$\Omega_b$	0.05	2
$\Omega_\Lambda$	0.685	2
$H_0$	$67.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$	2
$t_0$	13.8 Gyr	2

<sup>1</sup> 1 – Fixsen (2009), 2 – Ade et al. (2014)

Apart from the decays of dark matter particles, we investigated the processes of their annihilation. We showed that the influence of the annihilation of dark matter particles with an annihilation cross section  $\langle\sigma v\rangle_{\chi\bar{\chi}}^{\text{ann}} = 10^{-26} \text{ cm}^3 \text{ s}^{-1}$  (see, e.g., Jungman et al. 1996) in the case where the annihilation products are protons and antiprotons,  $\chi\bar{\chi} \rightarrow p\bar{p}$ , on the change in  $\eta$  on all the time scales of interest could be neglected. This implies the absence of the terms responsible for the annihilation of X- and  $\chi$ -particles in Eq. (7). The change in  $\eta$  attributable to the annihilation of dark matter particles with masses  $10 \text{ GeV}$ – $1 \text{ TeV}$  alone is negligible even at the epoch of Big Bang nucleosynthesis (at which the contribution from the annihilation is maximal):  $|\Delta\eta/\eta_{\text{BBN}}| < 10^{-13} \div 10^{-11}$  (the upper limit corresponds to a lower  $\chi$ -particle mass).

To determine the initial conditions for Eqs. (5) and (6), we introduce a parameter  $\alpha$  defining the fraction

(by the number of particles) of unstable dark matter particles in the entire dark matter at the epoch of Big Bang nucleosynthesis. For the range of lifetimes  $t_{\text{BBN}} \ll \tau \lesssim t_0$  we consider, the entire dark matter at the present epoch will be composed of stable  $\chi$ -particles some of which ( $\alpha$ ) were produced by the decays of X-particles and some  $(1 - \alpha)$  are the relic ones, i. e., the  $\chi$ -particle mass determines the initial conditions for the X-particles as well. The availability of reliable data on the parameter  $\eta$  at the epoch of Big Bang nucleosynthesis allows  $\eta_{\text{BBN}}$  to be used to determine the initial condition for Eq. (7). Thus, when solving the system of equations (5)–(7), we use the following initial conditions:

$$\begin{aligned} z^0 &= z_{\text{BBN}} = 10^9, \quad t^0 = \frac{1}{2H(z_{\text{BBN}})}, \\ n_{\text{p}}^0 &= \eta_{\text{BBN}} n_{\gamma}(z_{\text{BBN}}), \quad n_{\bar{\text{p}}}^0 = 0, \\ n_{\chi}^0 &= (1 - \alpha) \frac{\Omega_{\text{CDM}} \rho_{\text{c}}}{m_{\chi} c^2}, \quad n_{\bar{\chi}}^0 = \alpha \frac{\Omega_{\text{CDM}} \rho_{\text{c}}}{m_{\chi} c^2}, \end{aligned} \quad (8)$$

Let us write the system of equations (5)–(7) in a comoving volume that changes with time as  $\sim a^3$ , i. e.,  $\sim (1 + z)^{-3}$ :

$$\frac{dY_{\text{X}}}{dt} = -\Gamma Y_{\text{X}}, \quad (9)$$

$$\frac{dY_{\bar{\text{X}}}}{dt} = \Gamma Y_{\text{X}}, \quad (10)$$

$$\frac{dY_{\text{p},\bar{\text{p}}}}{dt} = -\langle \sigma v \rangle_{\text{pp}}^{\text{ann}} Y_{\text{p}} Y_{\bar{\text{p}}} (1 + z)^3 + B_h \Gamma Y_{\text{X}}, \quad (11)$$

where  $Y_i = n_i / (1 + z)^3$  is the number density of the  $i$ th type of particles in the comoving volume.

In such a form, Eqs. (9) and (10) have obvious analytical solutions that describe the evolution of the number densities of X- and  $\chi$ -particles in the comoving volume:

$$Y_{\text{X}}(t) = Y_{\text{X}}^0 e^{-t/\tau}, \quad (12)$$

$$Y_{\bar{\text{X}}}(t) = Y_{\bar{\text{X}}}^0 + Y_{\text{X}}^0 (1 - e^{-t/\tau}), \quad (13)$$

where  $Y_{\text{X}}^0 = n_{\text{X}}^0 / (1 + z^0)^3$  and  $Y_{\bar{\text{X}}}^0 = n_{\bar{\text{X}}}^0 / (1 + z^0)^3$  are the initial number densities of X- and  $\chi$ -particles in the comoving volume. Substituting solution (12),  $\Gamma = 1/\tau$ , and  $B_h = 1$  into Eq. (11), we obtain the final system of equations describing the evolution of the proton and antiproton number densities in the model under consideration:

$$\frac{dY_{\text{p},\bar{\text{p}}}}{dt} = -\langle \sigma v \rangle_{\text{pp}}^{\text{ann}} Y_{\text{p}} Y_{\bar{\text{p}}} (1 + z)^3 + \frac{Y_{\text{X}}^0}{\tau} e^{-t/\tau}. \quad (14)$$

The corresponding change in the baryon-to-photon ratio,

$$\frac{\Delta\eta(z)}{\eta_{\text{BBN}}} = \frac{\eta(z) - \eta_{\text{BBN}}}{\eta_{\text{BBN}}}, \quad (15)$$

determined from the solution of the system of equations (14) for  $m_{\chi} = 10 \text{ GeV}$ ,  $\alpha = 0.5$ , and various  $\tau$  is presented in Fig. 1a. Note that the parameters  $\alpha$  and  $m_{\chi}$  enter into the system of equations (14) in the form of a ratio. Therefore, the result presented in Fig. 1 also corresponds to the case of larger masses of dark matter particles provided that  $\alpha/m_{\chi}$  is conserved.

We see that the change in the baryon-to-photon ratio in the model under consideration for lifetimes  $\tau \gtrsim 10^{12} \text{ s}$

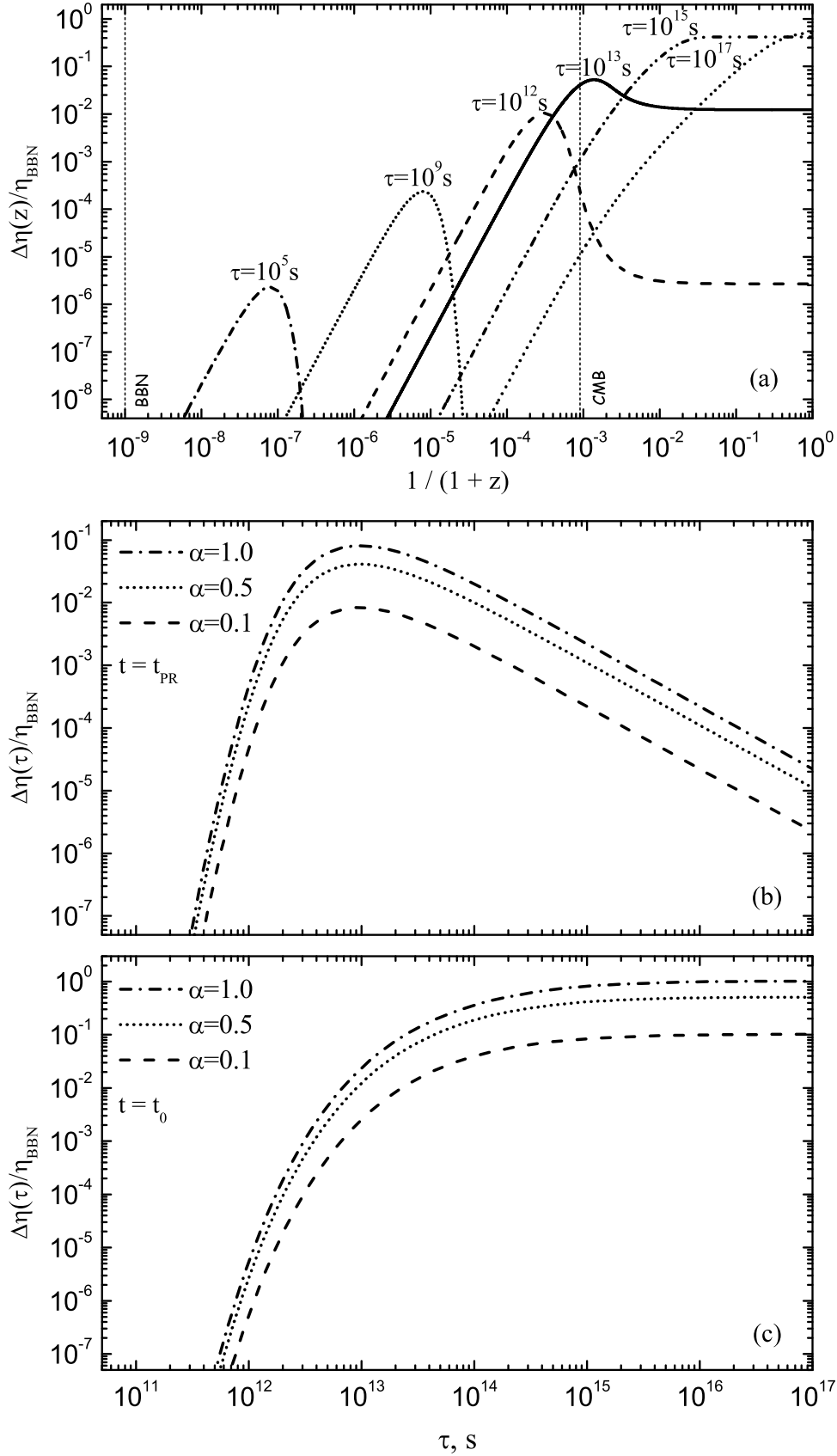
can reach  $\Delta\eta(z)/\eta_{\text{BBN}} \sim 0.01 - 1$ , which is a potentially observable value. We also see that the number densities of the protons and antiprotons in the comoving volume produced by late decays ( $\tau > 10^{13} \text{ s}$ ) in an already fairly expanded Universe freeze in such a way that  $\eta$  can differ significantly from  $\eta_{\text{BBN}}$  and  $\eta_{\text{CMB}}$  by the present epoch. Note, however, that in the decays  $\text{X} \rightarrow \chi \text{p}\bar{\text{p}}$  with the conservation of baryonic charge (i. e.,  $\Delta n_{\text{p}}(t) = \Delta n_{\bar{\text{p}}}(t)$ ),  $\Delta\eta/\eta_{\text{BBN}} \sim 1$  at the present epoch would imply almost equal numbers of protons and antiprotons in the Universe, while our Universe is significantly asymmetric in baryonic charge. The existence of such a number of antiprotons in the Universe would also give rise to an excess of the gamma-ray background from the annihilation of protons with antiprotons (see the next section).

Figure 1b presents the dependence  $\Delta\eta(\tau)/\eta_{\text{BBN}}$  of the change in  $\eta$  at the epoch of primordial recombination (the epoch for which the parameter  $\eta$  has been measured most precisely to date) on the lifetime of X-particles  $\tau$  for various  $\alpha$ . We see that the fraction of the change in  $\eta$  at this epoch can reach  $\Delta\eta/\eta_{\text{BBN}} \sim 0.01 - 0.1$ , which is also a potentially observable value. Figure 1c presents the dependence  $\Delta\eta(\tau)/\eta_{\text{BBN}}$  referring to the present epoch ( $t_0 \simeq 13.8 \text{ Gyr}$ ). We see that the decay of X-particles in the model under consideration leads to a significant change in the present baryon density for  $\tau > 10^{13} \text{ s}$ . However, the accuracy of its determination at an epoch  $z \sim 2 - 3$  and at the present epoch is still considerably lower than that for the epochs of Big Bang nucleosynthesis and primordial recombination.

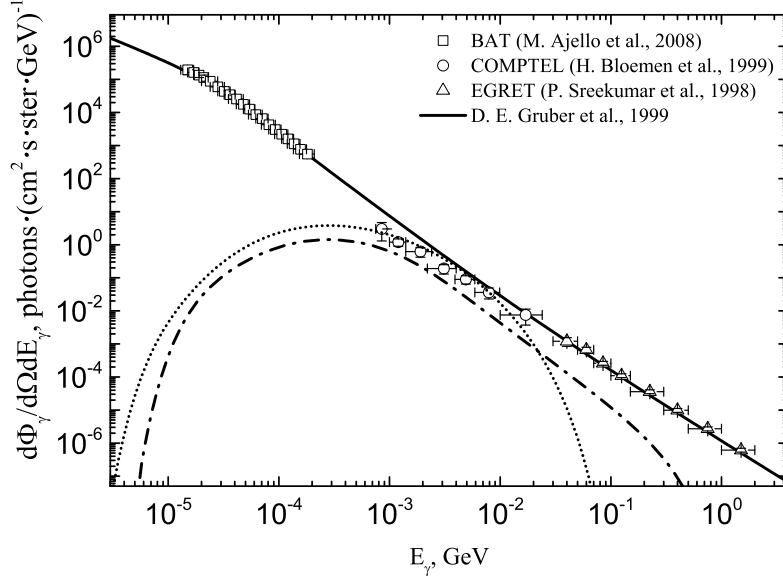
The results obtained should not come into conflict with other observational data:

- (1) The decays with a predominance of hadronic channels at early epochs  $\tau \ll t_{\text{PR}}$  can change significantly the chemical composition of the Universe (see, e.g., Jedamzik 2004; Kawasaki et al. 2005). The available observational data on the abundances of the primordial light elements (D,  $^4\text{He}$ ,  $^7\text{Li}$ ) agree well with the predictions of Big Bang nucleosynthesis calculations, which, in turn, limits the possibility of such a change.
- (2) The decays with  $\tau \sim t_{\text{PR}}$  can distort the CMB spectrum and affect the angular CMB anisotropy (see, e.g., Chen and Kamionkowski 2004; Chluba and Sunyaev, 2012). Comparison with observational data also allows the possible models to be constrained severely.
- (3) The hadronic decays with  $\tau \gtrsim t_{\text{PR}}$  can give rise to an excess gamma-ray background from the annihilation of produced antiprotons with background protons and directly from the decays of X-particles (see the next section).

In our case, we used data on the isotropic gamma-ray background to obtain constraints on the decays of particles with  $t_{\text{PR}} \lesssim \tau \lesssim t_0$ , because a maximal effect of change in the baryon-to-photon ratio is expected for such lifetimes of X-particles (see Fig. 1). As we will see, at present these constraints are more significant than those that can be given by present-day cosmological experiments.



**Figure 1.** Fraction of the change in the baryon-to-photon ratio  $\frac{\Delta\eta(z)}{\eta_{\text{BBN}}} = \frac{\eta(z) - \eta_{\text{BBN}}}{\eta_{\text{BBN}}}$  attributable to the decays of X-particles with lifetimes  $10^5 \text{ s} \leq \tau \leq 10^{17} \text{ s}$  ( $m_\chi = 10 \text{ GeV}$ ,  $\alpha = 0.5$ ); the vertical lines mark the epochs of Big Bang nucleosynthesis ( $z_{\text{BBN}} \sim 10^9$ ) and primordial recombination ( $z_{\text{PR}} \simeq 1100$ ). The dependence  $\Delta\eta(\tau)/\eta_{\text{BBN}}$  of the change in the baryon-to-photon ratio at the epoch of primordial recombination  $t = t_{\text{PR}}$  (b) and at the present epoch  $t = t_0$  (c) on the lifetime of X-particles for various values of the parameter  $\alpha$ .



**Figure 2.** Isotropic gamma-ray background  $d\Phi_\gamma/d\Omega dE_\gamma$  attributable directly to the decays of dark matter particles (dotted curve) and the annihilation of protons with antiprotons (dash-dotted curve) in the decay model of X-particles with a lifetime  $\tau = 10^{14}$  s under consideration ( $m_\chi = 10$  GeV,  $m_X - m_\chi = 10$  GeV,  $\alpha = 5 \cdot 10^{-6}$ ). The squares, circles, and triangles mark the experimental data taken from Ajello et al. (2008), Bloemen et al. (1999), and Sreekumar et al. (1998), respectively; the solid curve represents a fit to the experimental data from Gruber et al. (1999).

#### 4. CONSTRAINT ON THE POSSIBLE CHANGE IN $\eta$ ASSOCIATED WITH THE OBSERVATION OF AN ISOTROPIC GAMMA-RAY BACKGROUND

As was shown by Cirelli et al. (2011), apart from protons and antiprotons, photons and leptons will also be present among the end decay products of dark matter particles, with their fraction exceeding considerably the fraction of baryons even in the case of  $B_h = 1$  (i. e., when the decays completely run via hadronic channels). The reason is that apart from protons and antiprotons, mesons are produced in the hadronization process, which contribute to the photon and lepton components. In addition, the appearance of an antiproton fraction in the Universe will be accompanied by the formation of an additional gamma-ray background from the annihilation of proton-antiproton pairs. The main gamma-ray background as a result of such a process will arise from the decay of the  $\pi^0$  meson produced by the proton-antiproton annihilation (Stecker 1967; Steigman 1976). Both these processes, which can be represented schematically as

$$X \rightarrow \chi + \dots \begin{cases} \gamma + \gamma + \dots \\ p + \bar{p} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \\ \mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu), \end{cases} \end{cases} \quad (16)$$

will contribute to the isotropic gamma-ray background in the Universe.

We calculate the corresponding gamma-ray background by taking into account its extension to cosmological distances. Note that photons of different energies at different cosmological epochs interact differently with the medium in which they propagate (see, e. g.,

Zdziarski and Svensson 1989; Chen and Kamionkowski 2004). More specifically, there is a transparency window: the photons with energies  $E_\gamma < 10$  GeV emitted at epochs  $0 < z \lesssim 1000$  propagate almost without absorption and reach us in the form of an isotropic gamma-ray background. The formation of such a gamma-ray background is expected from the decays of X-particles with lifetimes  $t_{PR} \lesssim \tau \lesssim t_0$ .

The general formula describing the intensity of the isotropic gamma-ray background  $I_\gamma(E_\gamma)$  ( $\text{keV} \cdot \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1}$ ) from various processes is (see, e. g., Peacock 2010)

$$I_\gamma(E_\gamma) = E_\gamma \frac{d\Phi_\gamma}{d\Omega dE_\gamma} \quad (17)$$

$$= \frac{c}{4\pi} \int_0^{1000} dz \frac{\epsilon_\gamma([1+z]E_\gamma, z)}{H(z)(1+z)^4} e^{-\tau(E_\gamma, z)},$$

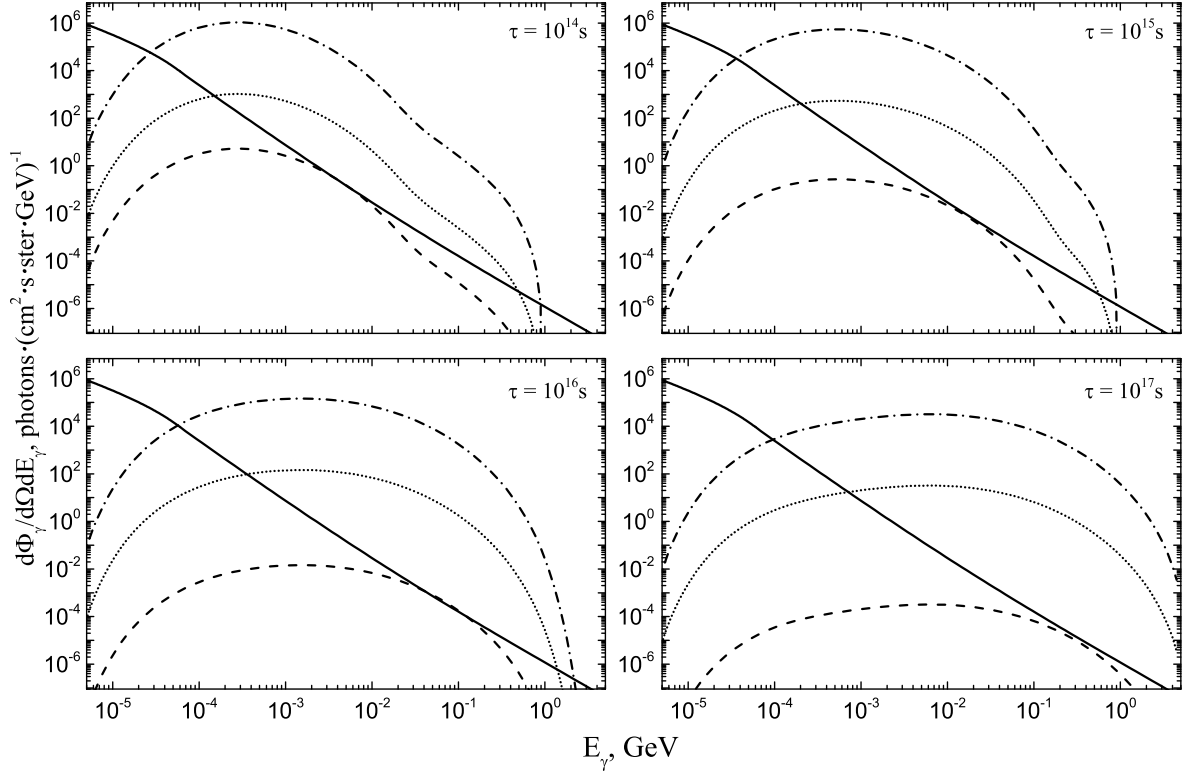
where  $\Phi_\gamma$  is the gamma-ray photon flux per unit time through a unit area,  $\tau(E_\gamma, z)$  is the optical depth describing the absorption of a photon emitted at epoch  $z$  with energy  $E_\gamma(1+z)$ ,  $\epsilon_\gamma$  is the volume emissivity that in our case is the sum of two terms,

$$\epsilon_\gamma(E_\gamma, z) = \epsilon_\gamma^X(E_\gamma, z) + \epsilon_\gamma^{\text{pp}}(E_\gamma, z), \quad (18)$$

describing the two contributions to the gamma-ray background mentioned above. The first term  $\epsilon_\gamma^X$  is related to the photons that are the X-particle decay products; the second term  $\epsilon_\gamma^{\text{pp}}$  is related to the photons that are the proton-antiproton annihilation products. These terms are described by the expressions

$$\epsilon_\gamma^X(E_\gamma, z) = E_\gamma \Gamma n_X(z) \frac{dN_\gamma}{dE_\gamma} \quad (19)$$

$$= E_\gamma \Gamma Y_X(z) (1+z)^3 \frac{dN_\gamma}{dE_\gamma},$$



**Figure 3.** Isotropic gamma-ray background  $d\Phi_\gamma/d\Omega dE_\gamma$  in the decay model of X-particles with lifetimes  $10^{14} \text{ s} \leq \tau \leq 10^{17} \text{ s}$  under consideration for  $\alpha = 1$  (dash-dotted curve),  $\alpha = 10^{-3}$  (dotted curve), and  $\alpha = \alpha_{\text{max}}$  (dashed curve) ( $m_\chi = 10 \text{ GeV}$ ,  $m_X - m_\chi = 10 \text{ GeV}$ ). The solid curve represents a fit to the experimental data from Gruber et al. (1999).

**Table 2.** Maximum admissible fraction of X-particles  $\alpha_{\text{max}}$  with various lifetimes  $\tau$  for  $\chi$ -particle masses of 10, 100, and 1000 GeV and the corresponding maximum admissible change in the baryon-to-photon ratio  $\Delta\eta/\eta_{\text{BBN}}$  at epoch  $z^*$ .

$\tau, \text{ s}$	$\alpha_{\text{max}}$			$\frac{\Delta\eta(z^*)}{\eta_{\text{BBN}}}$	$z^*$
	$m_\chi = 10 \text{ GeV}$	$m_\chi = 100 \text{ GeV}$	$m_\chi = 1000 \text{ GeV}$		
$10^{14}$	$5 \times 10^{-6}$	$5 \times 10^{-5}$	$5 \times 10^{-4}$	$2.3 \times 10^{-6}$	120
$10^{15}$	$5 \times 10^{-7}$	$5 \times 10^{-6}$	$5 \times 10^{-5}$	$4.2 \times 10^{-7}$	18
$10^{16}$	$10^{-7}$	$10^{-6}$	$10^{-5}$	$10^{-7}$	2.2
$10^{17}$	$10^{-8}$	$10^{-7}$	$10^{-6}$	$10^{-8}$	0

$$\epsilon_{\gamma}^{\text{p}\bar{\text{p}}}(E_\gamma, z) = E_\gamma \langle \sigma v \rangle_{\text{p}\bar{\text{p}}}^{\text{ann}} n_{\text{p}}(z) n_{\bar{\text{p}}}(z) \frac{dN_\gamma}{dE_\gamma} \quad (20)$$

$$= E_\gamma \langle \sigma v \rangle_{\text{p}\bar{\text{p}}}^{\text{ann}} Y_{\text{p}}(z) Y_{\bar{\text{p}}}(z) (1+z)^6 \frac{dN_\gamma}{dE_\gamma},$$

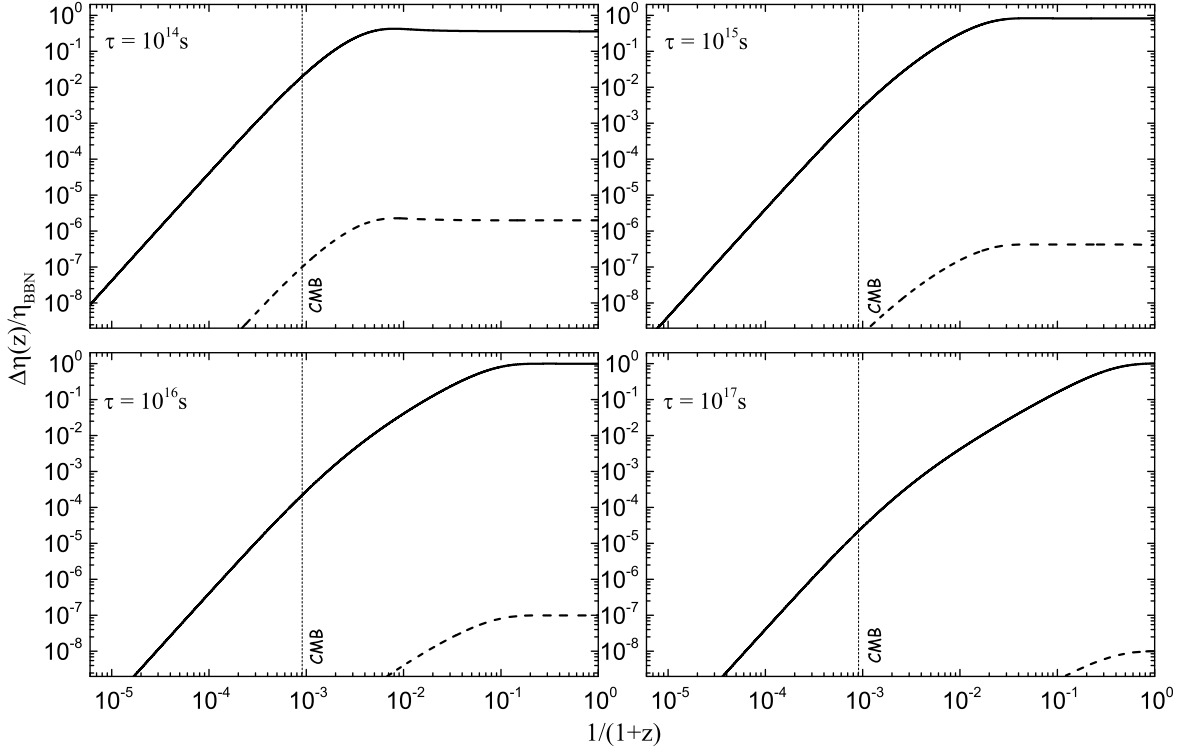
where  $dN_\gamma/dE_\gamma$  is the spectrum of the photons (phot·keV<sup>-1</sup>) emitted in one event of X-particle decay (in Eq. (19)) and proton-antiproton annihilation (in Eq. (20)).

In our calculations, we use the spectrum  $dN_\gamma/dE_\gamma$  of the photons that are the X-particle decay products calculated in the PYTHIA package. The numerical code for computing the spectra of the dark matter particle decay and annihilation products was taken from the site<sup>3</sup>; the details of using it can be found in Cirelli et

al. (2011). We use the data for  $m_X - m_\chi \sim 10 \text{ GeV}$  from the entire range of energy release accessible in the numerical code in such reactions, 10 GeV–200 TeV, to determine an upper bound on the possible change in  $\eta$ . The optical depths in (17) were also taken from this site. The spectrum  $dN_\gamma/dE_\gamma$  of the photons that are the proton-antiproton annihilation products was taken from Backenstoss et al. (1983).

For comparison, Fig. 2 presents the gamma-ray background  $d\Phi_\gamma/d\Omega dE_\gamma$  (phot·cm<sup>-2</sup>s<sup>-1</sup>sr<sup>-1</sup>keV<sup>-1</sup>) attributable to the contribution from each of the two terms in (18). The observational data on the isotropic gamma-ray background (10 keV–1 GeV) taken from Sreekumar et al. (1998), Bloemen et al. (1999), Gruber et al. (1999), and Ajello et al. (2008) are also presented in the figure. We see that the gamma-ray background directly from

<sup>3</sup> <http://www.marcocirelli.net/PPPC4DMID.html>



**Figure 4.** Fraction of the change in the baryon-to-photon ratio  $\frac{\Delta\eta(z)}{\eta_{\text{BBN}}} = \frac{\eta(z) - \eta_{\text{BBN}}}{\eta_{\text{BBN}}}$  attributable to the decays of X-particles with lifetimes  $10^{14} \text{ s} \leq \tau \leq 10^{17} \text{ s}$  ( $m_\chi = 10 \text{ GeV}$ ,  $m_\chi - m_{\bar{\chi}} = 10 \text{ GeV}$ ). The solid and dashed curves correspond to the fractions of X-particles  $\alpha = 1$  and  $\alpha = \alpha_{\text{max}}$ , respectively. The vertical line marks the epoch of primordial recombination ( $z_{\text{PR}} \simeq 1100$ ).

the decays of X-particles allow stringent constraints to be placed on the decay processes.

Figure 3 shows the total gamma-ray background  $d\Phi_\gamma/d\Omega dE_\gamma$  with the inclusion of both terms in (18) for X-particle lifetimes  $t_{\text{PR}} \lesssim \tau \lesssim t_0$  and various values of the parameter  $\alpha$ . The gamma-ray background admissible by the currently available observational data corresponds to  $\alpha_{\text{max}}$ , which characterizes the maximum admissible fraction of unstable X-particles with the corresponding lifetime. The values of  $\alpha_{\text{max}}$  for lifetimes  $t_{\text{PR}} \lesssim \tau \lesssim t_0$  are presented in Table 2.

Figure 4 presents the fraction of the change in the baryon-to-photon ratio corresponding to  $\alpha_{\text{max}}$  for various X-particle lifetimes (for comparison, Fig. 4 also presents this change for  $\alpha = 1$ ). We see that this change may reach  $\Delta\eta(z)/\eta_{\text{BBN}} \lesssim 10^{-5}$ . The present-day observational accuracy is  $\Delta\eta/\eta \sim 10^{-2} - 10^{-1}$ . Note that the corresponding number of antiprotons in the Universe at the present epoch related to  $\Delta\eta$  via the relation

$$\frac{n_{\bar{p}}}{n_p} \simeq \frac{1}{2} \frac{\Delta\eta}{\eta_{\text{BBN}}} \Big|_{z=0}$$

is consistent with the observational data on antiprotons in cosmic rays (see, e.g., Adriani et al. 2010).

Since the parameters  $\alpha$  and  $m_\chi$  enter into the system of equations (14) in the form of a ratio, the result obtained can be easily generalized to the case of larger masses of dark matter particles. For  $\chi$ -particles with masses  $m_\chi = 10, 100$ , and  $1000 \text{ GeV}$ , the derived parameter  $\alpha_{\text{max}}$  and the corresponding maximum change  $\Delta\eta/\eta_{\text{BBN}}$  in the baryon-to-photon ratio are listed in

Table 2. The table also gives the cosmological redshift  $z^*$  corresponding to the maximum change in  $\eta$ .

## 5. CONCLUSIONS

We investigated the influence of the baryonic decay channels of dark matter particles  $X \rightarrow \chi p \bar{p}$  on the change in the baryon-to-photon ratio at different cosmological epochs.

We showed that the present dark matter density  $\Omega_{\text{CDM}} \simeq 0.26$  is sufficient for the decay reactions of dark matter particles with masses  $10 \text{ GeV} - 1 \text{ TeV}$  to change the baryon-to-photon ratio up to  $\Delta\eta(z)/\eta_{\text{BBN}} \sim 0.01 - 1$  (Fig 1). However, such a change in  $\eta$  would lead to an excess of the gamma-ray background from the annihilation of proton-antiproton pairs, the decay products of dark matter particles, and from the gamma-ray photons produced directly in the decays of dark matter particles.

We used the observational data on the isotropic gamma-ray background to constrain the decay models of dark matter particles leading to a maximum effect of change in  $\eta$ : we determined the maximum admissible fraction of unstable dark matter particles with lifetimes  $t_{\text{PR}} \lesssim \tau \lesssim t_0$  and the change in  $\eta$  related to them. The maximum possible change in the baryon-to-photon ratio attributable to such decays is  $\Delta\eta(z)/\eta_{\text{BBN}} \lesssim 10^{-5}$  (Fig. 4).

Despite the fact that at present the data on the gamma-ray background constrain most severely the decay models of dark matter particles with the emission of baryons, the situation can change in future, with increasing accuracy of existing cosmological experiments



and the appearance of new ones. The detection of a change in the baryon-to-photon ratio in such experiments at a level of  $\lesssim 10^{-5}$  will serve as evidence for the existence of decaying dark matter particles, while its detailed study will be a powerful tool for studying their properties. In contrast, the constancy of the baryon-to-photon ratio will serve as a new source of constraints on the range of admissible parameters of dark matter particles.

## ACKNOWLEDGMENTS

We thank the referees for their valuable remarks. This work has been supported by the Russian Science Foundation (grant No 14-12-00955).

## References

- P.A.R. Ade, N. Aghanim, C. Armitage-Caplan, et al., *Astron. Astrophys.* **571**, 66 (2014).
- O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, et al., *Phys. Rev. Lett.* **105**, 121101 (2010).
- M. Ajello, J. Greiner, G. Sato, et al., *Astrophys. J.* **689**, 666 (2008).
- G. Backenstoss, M. Hasinoff, P. Pavlopoulos, et al., *Nucl. Phys. B* **228**, 424 (1983).
- G. Bertone, D. Hooper and J. Silk, *Phys. Rep.* **405**, 279 (2004).
- H. Bloemen, W. Hermsen, S.C. Kappadath, et al., *Astro. Lett. and Communications* **39**, 213 (1999).
- X. Chen and M. Kamionkowski, *Phys. Rev. D* **70**, 043502 (2004).
- J. Chluba and R.A. Sunyaev, *MNRAS* **419**, 1294 (2012).
- M. Cirelli, G. Corcella, A. Hektor, et al., *J. Cosmol. and Astropart. Phys.* **3**, 51 (2011).
- R.H. Cyburt, B.D. Fields and K.A. Olive, *J. Cosmol. and Astropart. Phys.* **11**, 12 (2008).
- D.J. Fixsen, *Astrophys. J.* **707**, 916 (2009).
- M. Fukugita and P.J.E. Peebles, *Astrophys. J.* **616**, 643 (2004).
- D.S. Gorbunov and V.A. Rubakov, *Introduction to the Early Universe: Hot Big Bang Theory* (LKI, Moscow, 2008; World Scientific, Singapore, 2011).
- D.S. Gorbunov and V.A. Rubakov, *Introduction to the Theory of the Early Universe: Cosmological Perturbations and Inflationary Theory* (LKI, Moscow, 2010; World Scientific, Singapore, 2011).
- D.E. Gruber, J.L. Matteson, L.E. Peterson, et al., *Astrophys. J.* **520**, 124 (1999).
- L. Hui, Z. Haiman, M. Zaldarriaga, et al., *Astrophys. J.* **564**, 525 (2002).
- A.V. Ivanchik, S.A. Balashev, D.A. Varshalovich et al., *Astron. Rep.* **92**, No 2 (2015).
- K. Jedamzik, *Phys. Rev. D* **70**, 063524 (2004).
- G. Jungman, M. Kamionkowski and K. Griest, *Phys. Rep.* **267**, 195 (1996).
- M. Kawasaki, K. Kohri and T. Moroi, *Phys. Rev. D* **71**, 083502 (2005).
- F. Nicastro, S. Mathur and M. Elvis, *Science* **319**, 55 (2008).
- J. A. Peacock, *Cosmological physics*, 9 ed. (Cambridge University Press, 2010).
- M. Rauch, *Ann. Rev.* **36**, 267 (1998).
- P. Sreekumar, D.L. Bertsch, B.L. Dingus, et al., *Astrophys. J.* **494**, 523 (1998).
- F. Stecker, *SAO Special Report No 261* (1967).
- G. Steigman, *Ann. Rev.* **14**, 339 (1976).
- G. Steigman, *JCAP* **10**, 16 (2006).
- G. Steigman, *Ann. Rev. Nucl. Part. Sci.* **57**, 463 (2007).
- C. Weniger, P.D. Serpico, F. Iocco, et al., *Phys. Rev. D* **87**, 123008 (2013).
- A.A. Zdziarski and R. Svensson, *Astrophys. J.* **344**, 551 (1989).